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TECHNICAL REPORT BRL-TR-3395

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ON THE EVALUATION OF  
GAS FLOW RESISTANCE MEASUREMENT  
THROUGH PACKED BEDS

C. K. ZOLTANI  
M. S. TAYLOR

SEPTEMBER 1992

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY  
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## 1. INTRODUCTION

Robbins and Gough (1978, 1979) investigated the sensitivity of the amplitude of the ignition induced pressure wave in a 5-in, 54-cal gun to the changes in the values of the friction factor  $\hat{f}_s$ . Nominal values of friction factor of 0.875, 1.75, and 3.5 were chosen for study. It was shown that a doubling of the friction factor has a strong effect on the smoothness of the pressure history. Large differences between breech and bore pressure for these three values of friction factor were calculated (e.g., the peak pressure difference observed for 3.5 was about 70% higher than for 1.75). Thus, the value of the friction factor used will have an important effect on the accuracy of the prediction of the interior ballistic flow.

In the following, a re-examination of the data which is the basis of one of the currently used bed drag correlation models is given. It is shown that, by minimizing the root-mean-square error (RMSE) between the data points and the proposed functional relationship, the accuracy in the prediction of the coefficient of drag of propellant beds can be improved.

## 2. ANALYSIS

Ergun (1952), Kuo and Nydegger (1978), and Jones and Krier (1983) have proposed models relating coefficient of drag and Reynolds number for gas flow through packed beds over the ranges illustrated in Figure 1. Following Jones and Krier, the relation between friction factor and coefficient of drag may be represented as  $\hat{f}_s = F_v [(1 - \phi)/Re]$ , where  $\phi$  is the porosity of the packed bed,  $F_v$  the coefficient of drag, and  $Re$  the Reynolds number of the gas flow based on particle size, with particle size much less than tube diameter.

In making the transition from the straight-line relation proposed by Ergun,

$$F_v = 150 + 1.75 \left( \frac{Re}{1 - \phi} \right), \quad (1)$$

to that of Kuo and Nydegger,

$$F_v = 276.23 + 5.05 \left( \frac{Re}{1 - \phi} \right)^{0.87}, \quad (2)$$

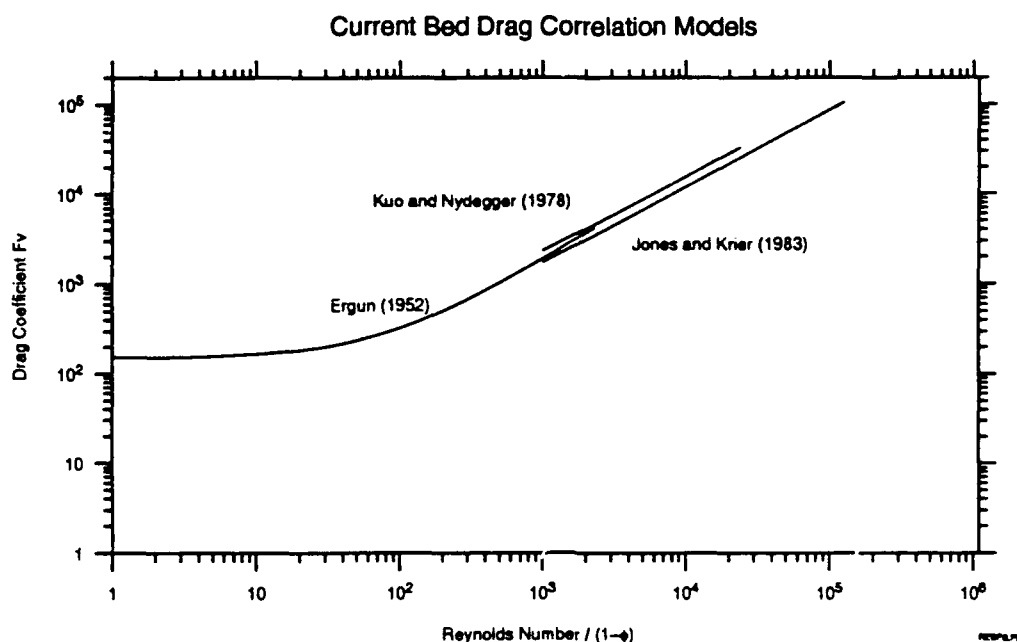


Figure 1. Proposed Models for Relating Coefficient of Drag and Reynolds Number.

a slight change in notation initiates substantial complications. Equation 1 is a simple linear model. Equation 2 is nonlinear. Nonlinearity complicates the statistical analysis of the data since determining appropriate choices for the parameters in Equation 2 becomes a computationally intensive optimization problem, and statistical inference about the resultant relation and the fitted parameters becomes much more tentative. The mathematical underpinnings of nonlinear regression will not support as much in the way of statistical inference or hypothesis testing as is available for linear regression. In general, nonlinear models (models in which one or more parameters appear nonlinearly) should be avoided unless there is a compelling reason for their use. Draper and Smith (1981) discuss this issue in some detail.

With the exception of data collected for 6-mm diameter beads, which are deferred to the Kuo and Nydegger model, Jones and Krier (1983) advance as a model relating coefficient of drag and Reynolds number,

$$F_v = 150 + 3.89 \left( \frac{Re}{1 - \phi} \right)^{0.87} . \quad (3)$$

Standard regression procedures used to model experimental data are developed under several assumptions. Fundamental among them is that the response (here  $F_v$ ) is measured with error but the predictors (here,  $Re$  and  $\phi$ ) are measured without error. Jones and Krier provide estimates of error in  $F_v$ ,  $Re$ , and  $\phi$ , indicating that this assumption is not met. In practice, this situation is often circumvented by arguing that the error in predictor measurement is small compared to the range of the predictor variables. This would appear to be the case here, but reliance on any resultant representation should be approached with caution.

This model was constructed for Reynolds numbers in excess of  $10^3$ , and for a larger variety of testing medium ( $D_b$ ) than heretofore considered. Residual plots of Equation 3 for the Jones (1980) data are shown in Figures 2 and 3. Residuals are defined as the differences  $F_{v_i} - \hat{F}_{v_i}$ ,  $i = 1, 2, \dots, n$ , where  $F_{v_i}$  is an experimentally determined value of drag coefficient, and  $\hat{F}_{v_i}$  is the corresponding value predicted by the regression equation. These plots are useful for assessing the adequacy of a fitted regression model and also serve as a diagnostic tool.

Figure 2 strongly suggests that another regression assumption may not be satisfied: The variance of the residuals does not appear constant over the range of  $Re' = \frac{Re}{1 - \phi}$ . Weighted least squares or a transformation on the observations  $F_{v_i}$  before regression are possible corrective procedures for this residual pattern. Figure 3 reaffirms the heterogeneity of variance concern, and shows, moreover, that the departure from the fitted equation is systematic with bead diameter  $D_b$ . The regression equation underestimates entire classes of measurements corresponding to  $D_b = 1.5, 3, 6$  mm, and overestimates for  $D_b = 2$  mm for measurements in a tube of 50.8 mm in diameter.

While nonlinear regression normally seeks to minimize the sum of the squared residuals, just as in ordinary linear regression, the computational procedures are iterative and may diverge or converge to local extrema. Furthermore, these procedures may be sensitive to specified initial conditions. Following a systematic selection of initial conditions, we determined that the equation

$$F_v = 61 + 2.7 \left( \frac{Re}{1 - \phi} \right)^{0.91} \quad (4)$$

provides an improved representation of the data modeled by Jones and Krier. The RMSE (an estimate of the standard deviation of the residuals and a commonly used measure for adequacy of fit) is 1,727,

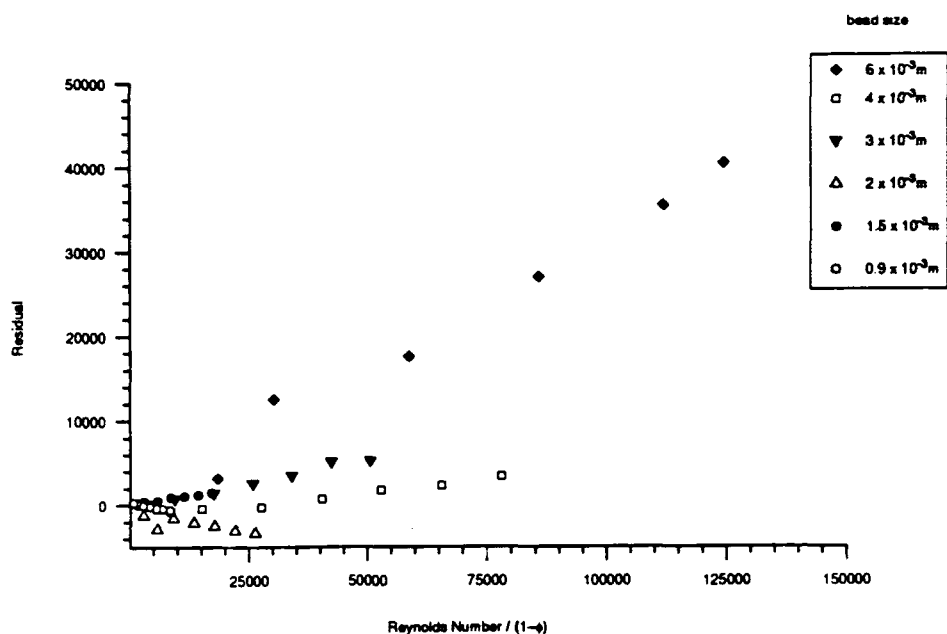


Figure 2. Residuals vs. Modified Reynolds Number.

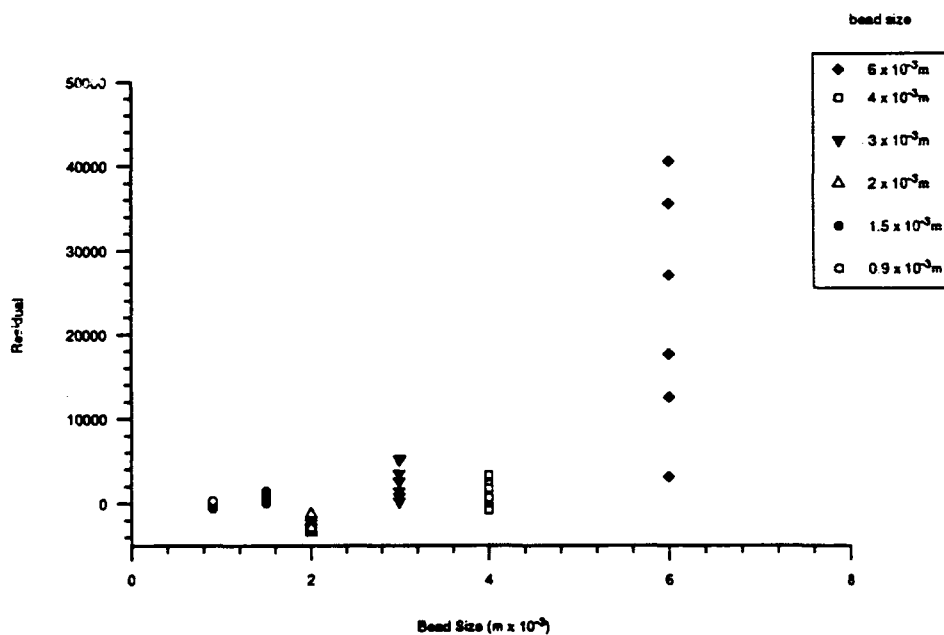


Figure 3. Residuals vs. Bead Size Corresponding to Equation 3.

compared to 2,144 for Jones and Krier's Equation 3; a reduction of 20%. If the data corresponding to  $D_b = 6$  (chief contributor to the heterogeneity of variance condition) is included in the regression, then the relation  $F_v = 2,750 + 0.272 (Re/1 - \phi)^{1.12}$  provides a two-thirds reduction in RMSE over that of Equation 3. The residual plot corresponding to Equation 4, shown in Figure 4, is improved, but the undesirable pattern of under(over) fitting classes of bead diameter still persists.

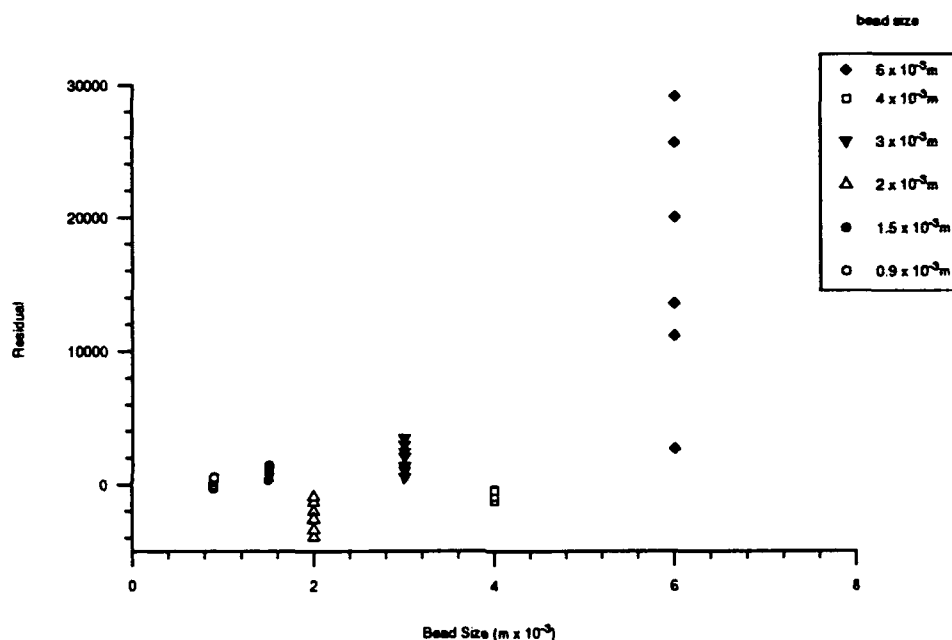


Figure 4. Residuals vs. Bead Size Corresponding to Equation 4.

The iterative procedure used to determine Equation 4 was a Gauss-Newton method with stephalving. This procedure, along with the Newton-Raphson method (which may be appropriate when the residuals are quite large) are commonly available as part of the nonlinear regression platform of current statistical software packages (e.g., JMP Version 2.0 Software, 1989).

An approximate confidence interval for the exponent of  $Re'$  in Equation 4 was determined using procedures detailed in Bates and Watts (1988) or Ratkowski (1990). A 95% confidence interval for the fitted exponent 0.91 is the interval [.84, .98]. Since this interval fails to cover unity, a straight-line relation like Ergun's for higher Reynolds numbers is not supported by these data.

Transforming the variables ( $Re'$ ,  $F_v$ ) by taking logarithms, as suggested by the residual plot in Figure 3, effectively linearizes the data. This was pointed out previously by Jones and Krier. In regression analysis, a measure of precision of the regression line which is often used in addition to RMSE is given by a statistic denoted as  $R^2$ . The value taken on by  $R^2$  in the unit interval  $[0, 1]$  quantifies the amount of variation in the response  $F_v$  accounted for by the regression line. Values close to one are highly desirable, indicating that the regression has effectively accounted for the variation in the response. The regression line determined after transformation of these data has an  $R^2$  value,  $R^2 = 0.98$ . Comparison between linear models and nonlinear models is difficult. RMSE values cannot be compared across the transformation, and a well defined  $R^2$  statistic for nonlinear models does not exist.

If an expression  $F_v = \beta_0 + \beta_1 (Re/1 - \phi)^{\beta_2}$  is the model of choice for relating Reynolds number and coefficient of drag for Reynolds number in excess of  $10^3$ , then Equation 4 would seem to be a strong candidate. Actually, none of the models considered captures the strong partitioning of the data according to bead diameter. An attempt to accommodate all the bead diameters using a single equation might be accomplished through the introduction of dummy variables (Draper and Smith 1981) to reflect the underlying physics, but only at the expense of considerable complication in the expression relating Reynolds number to coefficient of drag. Such an elaboration would not likely gain acceptance by the researcher.

### 3. RESULTS

An appreciation of the significance of the new relationship (Equation 4) may be gained by calculating the coefficient of drag at Reynolds number encountered in a typical interior ballistic simulation and comparing it with the value obtained from the Jones-Krier model (Equation 3). At  $\phi = 0.40$  and Reynolds number  $= 1.5 \times 10^5$ , this formulation gives  $F_v = 1.934 \times 10^5$ , while the suggested Equation 4 gives a value of  $2.206 \times 10^5$  (or  $\hat{f}_s = 0.882$ ), a 14% increase. As the Reynolds number increases, the difference becomes larger. We note, in Figure 5, that the new, statistically improved Equation 4 gives a consistently larger value of the drag coefficient than Equation 3.

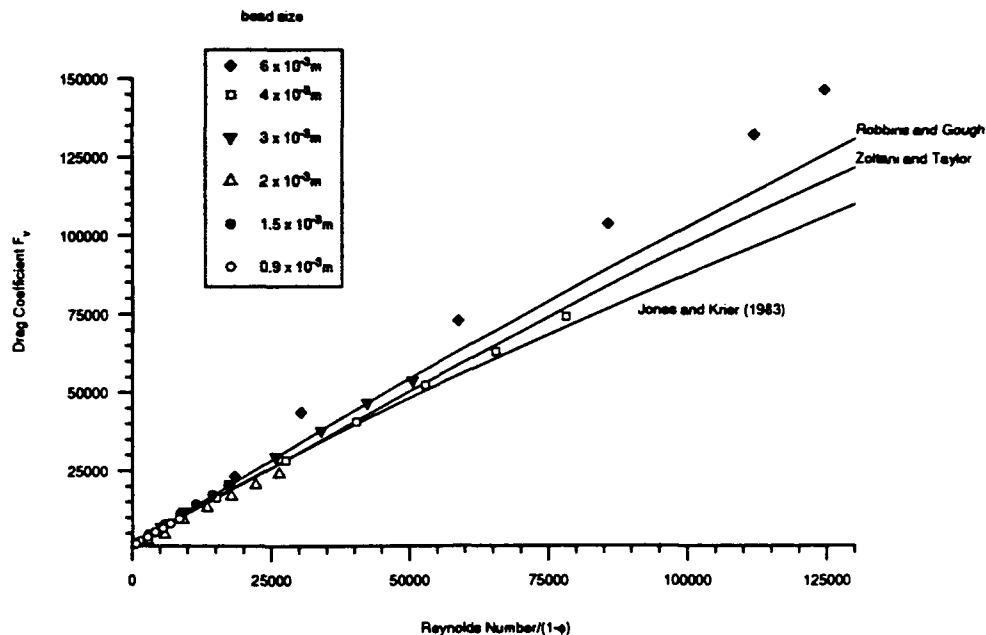


Figure 5. Drag Coefficient vs. Reynolds Number/(1 - φ).

#### 4. CONCLUSIONS

Keeping in mind the observation of Robbins and Gough (1978) about the sensitivity of the pressure smoothness and history to the friction factor, the difference in the calculated coefficient of drag from the two relationships (Equations 3 and 4) is judged to be significant. Significant, since consistent with current practice, these relationships are used to calculate the drag within the propellant bed. Indeed, it would be desirable to re-examine the functional form of the other popularly used coefficients of drag to see the difference in predicted values when the RMSEs are minimized.

G. E. P. Box, an influential contemporary statistician, has remarked that "No model is correct, but some are useful." It is in this spirit that we offer these remarks, along with the hope for an incremental move toward a more useful model.

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**APPENDIX**  
**DATA OF JONES (1980)**

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# REDUCED DATA FOR STEADY STATE EXPERIMENT

POROSITY = .4304    BEAD = 6.0    TEST DIA = 2.00

DEL P	PLENUM	TEMP	DENSITY	U AVG	MASS	RE	FV
68.200	225.000	19.000	.852	119.319	.954	70843.5	145395.3
68.200	225.000	19.000	.852	119.319	.954	70843.5	145395.3
61.010	200.000	16.000	.772	118.355	.858	63678.1	131576.9
47.060	150.000	14.000	.602	116.335	.658	48835.0	103254.6
32.310	100.000	11.000	.422	113.733	.450	33426.2	72512.9
17.500	50.000	11.000	.241	102.782	.233	17264.2	43459.7
8.900	25.000	11.000	.153	97.892	.141	10458.3	23206.6

RE/M*M	DB*RE/L*M*M	K*DB*RE/L*M*M
6310970.6	375629.0	122576.4
6310970.6	375629.0	122576.4
5706196.5	339632.8	110830.0
4498126.7	267728.5	87366.0
3187631.4	189727.8	61912.6
2015896.9	119988.2	39154.3
1346257.4	80129.2	26148.0

RE	ERGUN'S FV	KUO'S FV	FV CAL	ACTUAL FV
70843.5	217804.7	136956.7	105434.5	145895.3
70843.5	217804.7	136956.7	105434.5	145895.3
63678.1	195790.2	124847.2	96106.8	131578.9
48835.0	150187.4	99163.9	76322.8	103254.8
33426.2	102846.3	71381.4	54922.1	72512.9
17264.2	53191.4	40294.9	50976.3	43459.7
10458.3	32281.4	26151.1	20081.3	23208.8

LINE FIT TO DATA YIELDS

FV = 4345.733+

1.951RE/(1-POR)

# REDUCED DATA FOR STEADY STATE EXPERIMENT

POROSITY = .3863    BEAD = 4.0    TEST DIA = 2.00

DEL P	PLENUM	TEMP	DENSITY	U AVG	MASS	RE	FV
102.300	300.000	26.000	1.075	107.583	.975	47871.8	73657.4
85.780	250.000	22.000	.915	108.075	.818	40177.1	62840.8
69.700	200.000	19.000	.763	104.028	.660	32426.3	51900.0
53.550	150.000	18.000	.582	102.748	.504	24756.3	40370.9
36.750	100.000	16.000	.405	100.793	.344	16907.9	28243.0
20.000	50.000	15.000	.236	94.434	.188	9214.7	16405.4
10.400	25.000	15.000	.151	83.702	.107	5244.7	9624.8

RE/M\*M

DB\*RE/L\*M\*M

K\*DB\*RE/L\*M\*M

5371437.3  
4575164.4  
3800274.2  
2963894.6  
2089123.4  
1292569.0  
936445.1

211419.8  
180078.5  
149578.8  
116858.9  
82227.9  
50875.5  
36858.5

71343.6  
60767.4  
50475.3  
39366.5  
27747.8  
17167.9  
12437.9

RE	ERGUN'S FV	KUO'S FV	FV CAL	ACTUAL FV
47871.6	136058.4	91359.2	70310.9	73657.4
40177.1	114717.4	78480.6	60390.6	62640.8
32426.3	92815.4	65177.1	50142.9	51900.0
24756.3	70744.0	51595.0	39680.7	40370.9
16907.9	46364.0	37106.8	28520.5	28243.0
9214.7	26426.2	21996.8	16881.1	18405.4
5244.7	15105.8	13578.5	10396.7	9624.6

LINE FIT TO DATA YIELDS

FV = 2514.204+

1.481RE/(1-POR)

# REDUCED DATA FOR STEADY STATE EXPERIMENT

POROSITY = .3954    BEAD = 3.0    TEST DIA = 2.00

DEL P	PLENUM	TEMP	DENSITY	U AVG	MASS	RE	FV
98.800	300.000	19.000	1.107	86.879	.830	30554.0	53487.2
84.120	250.000	18.000	.946	85.139	.695	25587.4	46470.7
67.500	200.000	16.000	.768	84.337	.557	20518.1	37843.8
51.750	150.000	14.000	.594	82.588	.423	15573.6	29471.2
35.630	100.000	13.000	.413	80.875	.286	10602.1	20720.9
19.300	50.000	13.000	.237	75.384	.154	5681.0	12044.8
9.800	25.000	13.000	.149	66.032	.085	3134.8	6980.3

RE/M\*M

DB\*RE/L\*M\*M

K\*DB\*RE/L\*M\*M

5134026.4	151558.5	50717.7
4461711.8	131709.7	44076.1
3621070.9	106894.0	35771.6
2846233.5	84020.8	28117.2
2013574.2	59440.7	19891.6
1242514.3	36679.0	12274.5
893059.2	26383.1	8822.3

RE	ERGUN'S FV	KUO'S FV	FV CAL	ACTUAL FV
30554.0	88587.9	62710.8	48243.0	53487.2
25587.4	74212.2	53781.8	41385.0	46470.7
20518.1	59539.2	44430.8	34182.0	37843.8
15573.6	45227.3	35013.2	26907.8	29471.2
10602.1	30837.4	25136.4	19299.7	20720.9
5681.0	16593.6	14722.9	11278.2	12044.8
3134.6	9223.2	8888.1	6783.7	68980.3

LINE FIT TO DATA YIELDS

FV = 2204.642+

1.651RE/(1-POR)

# REDUCED DATA FOR STEADY STATE EXPERIMENT

POROSITY = .3724    BEAD = 2.0    TEST DIA = 2.00

DEL P	PLENUM	TEMP	DENSITY	U AVG	MASS	RE	FV
109.100	300.000	21.000	1.061	78.083	.873	16523.2	24050.2
91.830	250.000	19.000	.900	77.178	.564	13858.5	20475.8
74.410	200.000	18.000	.735	75.786	.452	11108.8	16695.9
56.700	150.000	17.000	.567	74.254	.342	8392.4	13140.3
39.070	100.000	16.000	.398	71.853	.232	5704.9	9357.0
20.900	50.000	16.000	.230	79.010	.148	3629.8	4552.0
10.100	25.000	15.000	.145	81.395	.072	1777.7	2830.8

RE/M\*M

DB\*RE/L\*M\*M

K\*DB\*RE/L\*M\*M

3462429.5

66140.6

23324.0

2950954.4

58074.8

19878.6

2444145.0

48100.8

16484.5

1917254.4

37731.8

12915.2

1387045.3

27297.1

9343.6

729852.5

14363.5

4916.5

589968.8

11810.8

3974.2

RE

ERGUN'S FV

KUO'S FV

FV CAL

ACTUAL FV

16523.2

46223.2

35679.9

27421.3

24050.2

13858.5

38792.9

30857.0

23552.2

20475.8

11108.8

31119.8

25335.1

19452.8

16895.9

8392.4

23551.3

19913.8

15276.7

13140.3

5704.9

16057.8

14312.2

10961.9

9357.0

3629.8

10270.9

9747.0

7445.3

4552.0

1777.7

5107.0

5365.9

4070.6

2830.9

LINE FIT TO DATA YIELDS

FV = 1101.441+

1.354RE/(1-POR)

# REDUCED DATA FOR STEADY STATE EXPERIMENT

POROSITY = .3900    BEAD = 1.5    TEST DIA = 2.00

DEL P	PLENUM	TEMP	DENSITY	U AVG	MASS	RE	FV
107.800	300.000	12.000	1.121	59.460	.567	10444.8	20374.0
90.690	250.000	11.000	.950	58.593	.474	8721.3	17393.6
73.200	200.000	9.000	.772	57.365	.377	6937.9	14339.7
56.250	150.000	8.000	.598	55.702	.283	5219.4	11348.3
36.680	100.000	8.000	.416	54.423	.193	3545.4	7982.8
20.300	50.000	8.000	.237	48.717	.098	1807.9	4682.7
10.200	25.000	8.000	.151	42.972	.055	1017.8	2667.4

RE/M*M	DB*RE/L*M*M	K*DB*RE/L*M*M
3657128.2	53979.2	18151.9
3133575.5	46251.6	15553.3
2582378.4	38115.9	12817.5
2053178.4	30304.9	10190.8
1460965.9	21563.9	7251.4
929718.5	13002.6	4614.5
672742.8	9029.7	3339.1

RE	ERGUN'S FV	KUO'S FV	FV CAL	ACTUAL FV
10444.8	30114.7	24626.2	18908.7	20374.0
8721.3	25170.0	21090.4	16183.1	17393.6
6937.9	20053.8	17334.0	13289.6	14339.7
5219.4	15123.6	13592.4	10407.4	11348.3
3545.4	10321.1	9787.9	7476.8	7982.8
1807.9	5336.6	5570.3	4228.0	4682.7
1017.8	3070.0	3487.9	2623.9	2667.4

LINE FIT TO DATA YIELDS

FV = 1195.945+

1.774RE/(1-POR)

# REDUCED DATA FOR STEADY STATE EXPERIMENT

POROSITY = .3804    BEAD = .9    TEST DIA = 2.00

DEL P	PLENUM	TEMP	DENSITY	U AVG	MASS	RE	FV
110.700	300.000	21.000	1.100	48.457	.442	5199.9	9642.4
92.260	250.000	21.000	.917	47.529	.363	4259.9	8177.7
74.290	200.000	21.000	.741	48.955	.289	3391.2	6678.0
57.440	150.000	19.000	.576	45.000	.215	2529.7	5387.6
39.560	100.000	19.000	.401	42.882	.143	1678.2	3893.9
21.500	50.000	18.000	.234	36.574	.071	833.7	2481.2
11.400	25.000	17.000	.152	29.824	.038	440.7	1613.4

RE/M*M	DB*RE/L*M*M	K*DB*RE/L*M*M
2827830.1	26636.2	9041.5
2397905.3	22588.3	7666.9
1964152.7	18502.3	6280.1
1584390.2	14925.0	5065.8
1157494.8	10903.8	3700.9
787762.2	7420.7	2518.7
624080.1	5878.8	1995.4

RE	ERGUN'S FV	KUO'S FV	FV CAL	ACTUAL FV
5199.9	14838.5	13370.1	10238.1	9642.4
4259.9	12181.8	11284.7	8629.8	8177.7
3391.2	9728.2	9303.8	7103.8	6678.0
2529.7	7295.0	7271.9	5538.7	5387.8
1678.2	4889.9	5171.4	3920.7	3893.9
833.7	2504.7	2939.6	2201.6	2481.2
440.7	1394.7	1805.7	1328.2	1613.4

LINE FIT TO DATA YIELDS

FV = 759.821+

1.621RE/(1-POR)

## LIST OF SYMBOLS

$D_b$	= particle diameter
$\hat{f}_s$	= friction factor
$F_v$	= coefficient of drag
$F_{v_i}$	= <i>i</i> th observed value of the drag coefficient
$\hat{F}_{v_i}$	= predicted drag coefficient corresponding to the <i>i</i> th observed value
$Re$	= Reynolds number based on particle size
$Re'$	= Reynolds number divided by $1-\phi$
$\beta_0$	= model coefficient
$\beta_1$	= model coefficient
$\beta_2$	= model exponent
$\phi$	= porosity of the packed bed

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